

Observation of mesoscopic conductance fluctuations in YBaCuO grain boundary Josephson Junctions

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Magneto-fluctuations of the normal state resistance R_N have been reproducibly observed in high critical temperature superconductor (*HTS*) grain boundary junctions, at low temperatures. We attribute them to mesoscopic transport in narrow channels across the grain boundary line. The Thouless energy appears to be the relevant energy scale. Our findings have significant implications on quasiparticle relaxation and coherent transport in *HTS* grain boundaries.

Junctions are extremely useful to test very important properties of high critical temperature superconductors (*HTS*) [1, 2, 3], whose nature has not yet been completely established [4]. Recently high quality YBa₂Cu₃O_{7- δ} (*YBCO*) grain boundary (*GB*) Josephson junctions (*JJs*) have given the first evidence of potentials to study exciting crucial issues such as macroscopic quantum behaviors, coherence and dissipation [5, 6]. The quantum tunnelling of such macroscopic *d* - wave devices out of zero voltage state has been demonstrated along with the quantization of its energy states. The cross-over temperature between quantum and classical regimes was found to be of the order of 40 *mK*. This is evidence of the fact that despite the short coherence lengths in a highly disordered environment and the presence of low energy (nodal) quasiparticles (*qps*) due to the nodes of the *d* - wave order parameter symmetry [1, 3, 5], dissipation in a *HTS* junction does not seem to be as disruptive for the quantum coherence at low temperatures, as one would naively expect. Increasing the available information about the nature of *qps* and their relaxation processes is of crucial importance to unveil the mechanism which leads to superconductivity in *HTS*.

In this letter we report on transport measurements of *YBCO* biepitaxial (*BP*) *GB* junctions (see scheme in Fig. 1a), which give evidence of conductance fluctuations (*CFs*) in the magneto-conductance response of *HTS* junctions. To our knowledge, this is the first time that *CFs* are measured in *HTS* junctions. Our results prove the appearance of mesoscopic effects in the unusual energy regime $k_B T \ll \epsilon_c < eV < \Delta$. Here $k_B T$ is the thermal energy at temperature *T*, ϵ_c is the Thouless energy introduced below, *V* is the applied voltage and Δ is the superconducting gap (≈ 20 *meV* for *YBCO* [1]).

The progress registered in mesoscopic physics in the last two decades is impressive [7, 8, 9, 10]. At low tem-

peratures, quantum coherence can be monitored in the conductance *G* of a normal metallic sample of length L_x attached to two reservoirs. The electron wave packets that carry current in a diffusive wire have minimum size of the order of $L_T > L_x \gg l$. Here *l* is the electron mean free path in the wire and L_T is the thermal diffusion length $\sqrt{\hbar D / k_B T}$ (*D* is the diffusion constant). The first inequality is satisfied at relatively low temperatures as far as $k_B T \ll \epsilon_c \equiv \hbar D / L_x^2$. At low voltages ($eV \ll \epsilon_c$), the system is in the regime of universal conductance fluctuations: the variance $\langle \delta g^2 \rangle$ of the dimensionless conductance $g = G / 2e^2 / \hbar$ is of order of unity. Mesoscopic phenomena have been widely investigated even in metallic wires interrupted by tunnel junctions [11] and in Josephson junctions [12, 13, 14]. In experiments on *Nb/Cu/Nb* long junctions [14], phase coherence mediated by Andreev reflection at the *S/N* interfaces, has been shown to persist in the whole diffusive metallic channel, several hundreds of *nm* long. Such an effect is robust with respect to energy broadening due to temperature, but it is expected to be fragile to energy relaxation processes induced by the applied voltage. By contrast, in our case, the *qp* phase coherence time τ_φ seems not to be limited by energy relaxation due to voltage induced non-equilibrium. Mesoscopic resistance oscillations are found even for $eV > \epsilon_c$, indicating that *qps* do not loose coherence at low temperatures, while diffusing across the *N* bridge. By plotting the auto-correlation function of the measured *CF* in magnetic field *H* (see below), we determine ϵ_c , in analogy to similar studies of normal metal and semiconductor systems [10, 15]. It is valuable that *HTS GB JJs* make accessible this regime, which is not commonly achieved by conventional metals and junctions, providing a “direct” measurement of the Thouless energy.

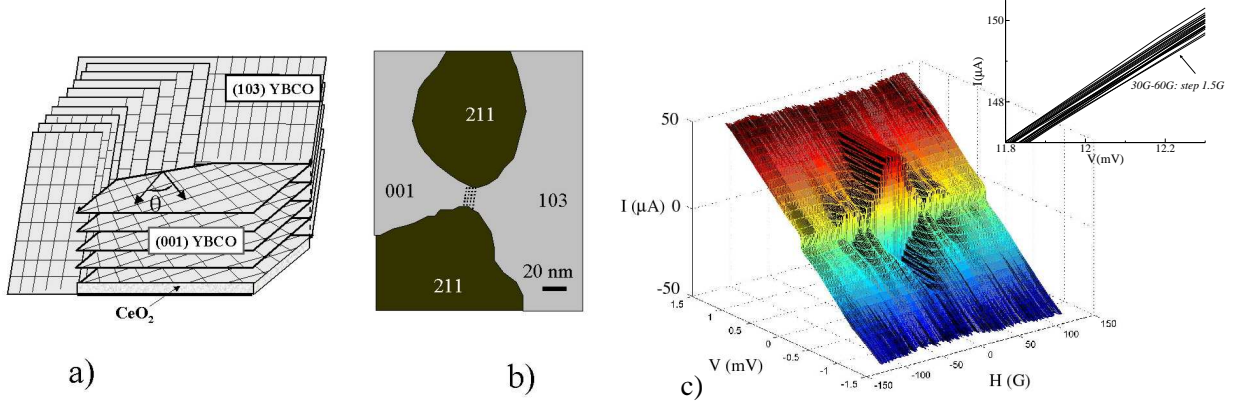


FIG. 1: (a) Sketch of the grain boundary structure for three different interface orientations. (b) Sketch of a typical mesoscopic channel, that might be generated at the grain boundary line (dotted lines) because of the presence of impurities. In biepitaxial junctions, the impurities may be due to Yttrium excess. (c) $I - V$ curves as a function of the magnetic field H : the Fraunhofer pattern indicates a uniform interface with critical current density $J_C \sim 8 \times 10^4 \text{ A/cm}^2$ at $T = 4.2 \text{ K}$. In the inset, a few $I - V$ curves are displayed at different magnetic fields (from 30 G to 60 G, step 1.5 G) at high voltages to give a better evidence of the fluctuations of the resistance.

The *BP JJs* are obtained at the interface between a (103) YBCO film grown on a (110) SrTiO₃ substrate and a *c*-axis film deposited on a (110) CeO₂ seed layer (Fig. 1a). The presence of the CeO₂ produces an additional 45° in-plane rotation of the YBCO axes with respect to the in-plane directions of the substrate. By suitable patterning of the CeO₂ seed layer, the interface orientation can be varied and tuned to some appropriate transport regime (in Fig. 1a we have indicated the two limiting cases of 0° and 90°, and an intermediate situation defined by the angle θ , in our case $\theta = 60^\circ$) [6, 16]. We have selected junctions with sub-micron channels, as eventually confirmed by Scanning Electron Microscope analyses, and measured their $I - V$ curves, as a function of H and T . We have investigated various samples, but here we focus mostly on the junction characterized by the Fraunhofer magnetic pattern shown in Fig. 1c, where it is more likely that only one uniform superconducting channel is active [17]. In Fig. 1c the I/V curves are reported in a 3d-plot as a function of magnetic field H . The critical current (I_C) oscillations point to a flux periodicity which is roughly consistent with the typical size (10 – 100 nm) that we expect for our microbridge from structural investigations (see Fig. 1b). We have to take into account that the London penetration depth in the (103) oriented electrode is of the order of a few microns (much larger than the one in *c*-axis YBCO films)(see [5] for instance).

In low- T_c *JJs*, R_N represents the resistance at a voltage a few times larger than the gap values. This matter is more delicate when dealing with *HTS JJs*, because of the deviations from the ideal RSJ-like behavior [2, 3].

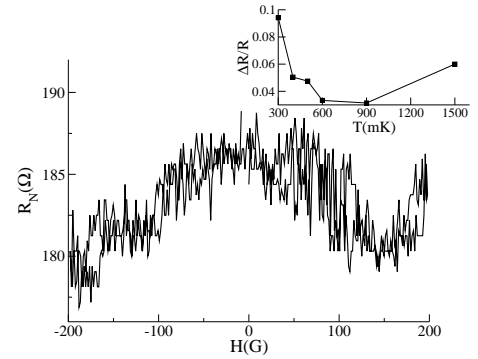


FIG. 2: Resistance R_N vs H at $T = 300 \text{ mK}$. Marked non periodic fluctuations are evident. In the inset, the zero field amplitude of the fluctuations is reported vs T .

In our case a linear branch typical of the RSJ behavior starts at $V = 5 \text{ mV}$. Values of V between 10 mV and 15 mV are representative for the problem we are investigating (see the inset of Fig. 1c). The average resistance \overline{R}_N over the whole magnetic field range is $\sim 182 \Omega$. We choose $V \approx 12 \text{ mV}$ for deriving the R_N vs. H curve, that is reported in Fig. 2 at the temperature $T = 300 \text{ mK}$ in the interval $[-200 \text{ G}, 200 \text{ G}]$. AC magneto-conductance measurements basically give the same results, but provide a more reliable Fourier transform, as we will discuss elsewhere. The dynamical resistance is measured at fixed bias current. Conductance fluctuations, as those shown in Fig. 2 become appreciable at temperatures below 900 mK ($k_B T \ll \hbar I_C / 2e$), in the whole magnetic field range. Their amplitude is $\sqrt{\langle (\delta G)^2 \rangle} \sim 0.07 \overline{G}_N$

(with $\overline{G}_N \equiv (\overline{R}_N)^{-1}$) at 300 mK and are more than one order of magnitude larger than the noise. Below 1.2 K, the fluctuations are nonperiodic, and for sure not related to the $I_C(H)$ periodicity, and have all the typical characteristics of mesoscopic fluctuations. The pattern shows occasionally some hysteresis mostly at high magnetic fields, when sweeping H back, which we attribute to some delay in the magnetic response. Above 1.2 K, thermal fluctuations dominate (see the inset in Fig. 2).

By performing the ensemble average of G_N over H , additional insights can be gained. The auto-correlation function is defined as:

$$\Delta G(\delta V) = \frac{1}{N_V} \sum_V \sqrt{\langle (G_{V+\delta V}(H) - \overline{G}_N)(G_V(H) - \overline{G}_N) \rangle_H} \quad (1)$$

with $\Delta G(0) = \sqrt{\langle (\delta G)^2 \rangle}$. Here N_V is the number of δV intervals in which the range $V \in (10 - 15 \text{ mV})$ has been divided. $\Delta G(\delta V)$ is reported in Fig. 3 at various temperatures. The plots are the results of an average over various series of measurements, to suppress sample specific effects.

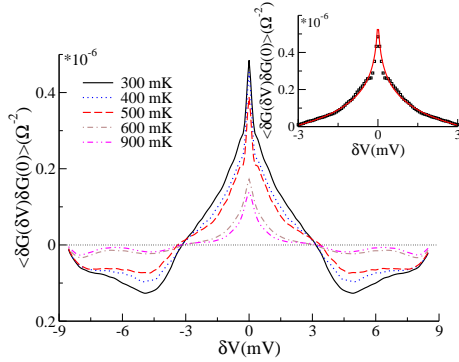


FIG. 3: The autocorrelation function of Eq.(1) is derived from experimental data for different temperatures. In the inset the autocorrelation function at T= 300 mK is fitted on the basis of Eq.2 (full line)

As we show in the inset of Fig. 3, this autocorrelation function is well described by a fit based on the standard theory for transport of diffusions modes in mesoscopic channels [8]. The effect of the applied H on the interference is expected to rule out contributions to the conductance fluctuations due to cooperons. The autocorrelation as a function of the phase change $\Delta\varphi$ is:

$$\langle \delta G(\Delta\varphi) \delta G(0) \rangle = \sum_{m=-\infty}^{\infty} \langle G_m G_{-m} \rangle e^{im\Delta\varphi} \approx \frac{2N}{3\pi} \left(\frac{2e^2}{h} \right)^2 \frac{\epsilon_c}{k_B T} \frac{L_y L_z}{L_x L_T} \Re \left\{ \ln \left(1 - e^{-(\xi + i\Delta\varphi)} \right) \right\} \quad (2)$$

Here the parameter $\xi = \pi L_x / L_T$ contains the important information on the channel effective length with respect to L_T (N is a constant of the order 1, up to higher orders in $e^{-|m|\xi}$). In deriving eq.(2) we have assumed $k_B T \gg \hbar / \tau_\varphi$ and larger than the level spacing in the microbridge [18]. The Fourier components of the auto-correlation $\langle G_m G_{-m} \rangle$, in the limit of small m 's, are $\langle G_m G_{m'} \rangle \propto \delta_{m',-m} \text{erfc} \left(\sqrt{|m|\xi} \right) e^{-|m|\xi/|m|}$. The exponential integral function erfc , together with the $\delta_{m',-m}$, arises from the sum over the diffusion modes. Correlations at larger $\Delta\varphi$ have to blur out due to other

mechanisms of dephasing not included here and cannot follow eq.(2). In the inset of Fig. 3 the full line shows the best fit obtained by using Eq.(2) with $\Delta\varphi = \sqrt{e\delta V / \epsilon_c}$ and $\xi = 0.1$. This value of $\xi = 0.1$ is consistent with a L_x value of the order of 50 nm. The value of ϵ_c can be read out of the plot from the location of the node, giving ϵ_c of the order of 3 meV. Our plots can be compared to the ones of ref.[11] obtained for a $Al/Al_2O_3/Al$ tunnel junction at $T = 20 \text{ mK}$, $V = 0.8 \text{ mV}$ in a magnetic field $H = 0.5 \text{ Tesla}$ which drives the junction into the normal state. In ref.[11], the energy broadening extracted from

the experiment, $\sim \max\{\hbar/\tau_\varphi, \epsilon_c\}$, is $2.3 \mu\text{eV}$, at 20mK .

In our case, $\langle (\overline{\Delta\varphi})^2 \rangle \approx e\overline{\delta V}/\epsilon_c \sim 1$ fixes the scale of amplitude of the voltage fluctuations $\overline{\delta V}$ for carriers diffusing across the bridge. It is remarkable that the coherence time which is expected when dephasing is dominated by small-energy-transfer (Nyquist) scattering of nodal *qps* ($\sim \hbar/V$ [19]) is much shorter than \hbar/ϵ_c . The voltage drop appears to occur mainly away from the microbridge as the electrochemical potential cannot change significantly over distances smaller than the wave packet size [20, 21]. We have found that both temperature and bias voltages up to 30 meV reduce the amplitude of the *CFs* (see the inset of Fig. 2) and of ϵ_c , but they do not wash out the correlations. $\sqrt{\langle (\delta G/\overline{G}_N)^2 \rangle}$ drops with temperature, according to eq.(2) as probed from the experiment (see inset of Fig.2).

Given that the thermal diffusion length $L_T \sim 0.13 \mu\text{m}$ at 1 K (with $D \sim 20 \div 24 \text{ cm}^2/\text{sec}$ for *YBCO*[22]), the condition $L_x < L_T$ is certainly met, thus confirming that ϵ_c is the relevant energy scale. The phase coherence length exceeds the size of the microbridge and therefore thermal decoherence can be ruled out. Hence, not only the interference of tunnelling currents takes place, which provides the Fraunhofer pattern of Fig. 1 *c*, but also the quantum interference of electrons returning back to the junction in their diffusive motion at the *GB*. We believe, this is the first time that the wave-like nature of the carriers fully appears in *HTS* systems and that mesoscopic scales can be identified.

As a final remark, our measurements show that ϵ_c is the relevant energy scale for the supercurrent as well. Indeed, we find that $eI_c R_N$ and ϵ_c are of the same order of magnitude, in agreement with the typical values measured in *HTS JJs* [2, 3] and the results on diffusive phase-coherent normal-metal *SNS* weak links [14, 23]. This feature gives additional consistency to the whole picture, relating the critical current, which is mediated by subgap Andreev reflection, with the transport properties at high voltages. The coherent diffusive regime across the *S/N/S* channel of our *GB* junctions persists even at larger voltage bias $\Delta > eV > \epsilon_c$ and is the dominating conduction mechanism. Hence, microscopic features of the weak link appear as less relevant, in favour of mesoscopic, non local properties. The results define important attributes of the role of grain boundaries in the transport in *HTS* junctions and in particular of the narrow self-protected channels formed in the complex growth of the oxide grain boundary [2, 3, 24, 25]. The fact that the dominant energy scale is found to be $\epsilon_c \sim 3 \text{ meV}$ sets a lower bound to the relaxation time at low T for *qps* of energy even ten times larger, of the order of picoseconds. It has been argued that antinodal *qps* may require slow diffusive drift of momentum along the Fermi surface towards the nodes of the *d-wave* gap [22, 26].

In conclusion, we have given evidence of conductance fluctuations in *HTS* grain boundary Josephson Junctions constricted by one single micro-bridge at low temperatures. *CFs* are the signature of a coherent diffusive regime. Our results seem to suggest an unexpectedly long *qps* phase coherence time and represents another strong indication that the role of dissipation in *HTS* has to be revised.

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